Zero stability of spinning rotor vacuum gages

K. E. McCulloh, S. D. Wood, and C. R. Tilford
Center for Basic Standards, National Bureau of Standards, Gaithersburg, Maryland 20899

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Spinning rotor vacuum gages measure pressure by determining the rate of slowing of a magnetically suspended spinning ball over and above the slowing caused by a pressure independent residual drag. For accurate measurement in the high vacuum range, this residual drag must be determined and subtracted as an offset correction. The stability of this residual drag, temperature induced changes of the ball's moment of inertia, vibration, and random measurement noise will determine the limits of stability and hence, the lowest usable pressure of the gage. Selected balls in a quiet, stable environment have demonstrated instabilities as low as $\pm 10^{-6}$ Pa (10^{-8} Torr) equivalent nitrogen pressure. However, instabilities as large as two orders of magnitude greater can occur. Examples are given of different types of instabilities and guidelines are presented for minimizing many of the sources of instability.

I. INTRODUCTION

Molecular drag vacuum gages have been proposed and developed since the middle of the last century. The development of magnetic suspensions in the first half of this century permitted the use of freely rotating bodies, a significant advance over the earlier oscillating devices. Refinement of the magnetic suspension during the last 15 years led to the commercial productions of such gages in 1981. Known variously as viscosity gages, or spinning rotor gages (SRG), these gages are probably more stable and predictable than other commercial high vacuum gages.

For many applications, it is desirable to make measurements at as low a pressure as possible. The lowest pressure measurable with an SRG will be limited by short term random noise, temperature instabilities, and changes in a magnetically induced residual drag. In this paper, we describe these various effects and present examples illustrating their magnitudes and characteristics.

II. DESCRIPTION OF THE SRG

A large number of publications exist on molecular drag gages, and the SRG in particular, of which we will cite only a few. An account of the historical development of molecular drag gages is contained in Ref. 1 and the magnetic suspension used in the SRG is described in Ref. 2. Further descriptions of the SRG are contained in Refs. 3 and 4. Briefly, the SRG levitates a small steel ball bearing (typically 4.5 mm diam) using permanent magnets and electromagnets, with inductive sensing and electronic feedback to provide suspension stability along all three axes. The ball is contained within a nonmagnetic thimble attached to the vacuum system. The suspension magnets and associated sensing coils are outside the thimble. A high frequency two-phase inductive drive spins the ball to approximately 400 Hz. The rotation of the ball is sensed by inductive pickup of the rotating component of the ball's magnetic moment. The pickup coils are located in the suspension head outside the thimble. The pickup signal is amplified and the rotational period of the ball is timed.

In the molecular flow regime, which extends up to about 1 Pa (1 Torr = 133 Pa) for an SRG, the fractional rate of slowing of the spinning ball due to collisions with gas molecules can be derived from molecular dynamics and classical mechanics,

$$-\dot{\omega}/\omega = C^{-1}P + 2\alpha\dot{T} + RD, \tag{1}$$

where ω is the angular velocity of the ball, $\dot{\omega}$ its time derivative, C a calibration constant whose value depends on the nature of the ball and the physical properties of the gas, P the pressure, α the linear coefficient of thermal expansion for the ball, $\dot{T}$ the time derivative of the ball's temperature, and RD is a pressure independent residual drag. The term $2\alpha\dot{T}$ accounts for temperature induced changes in the moment of inertia. For our steel ball, α is $1.2\times10^{-5}\ \mathrm{K}^{-1}$. The residual drag has a number of sources.[5] However, the dominant effects are eddy currents induced in the spinning ball by asymmetries in the suspension field and eddy currents induced in surrounding metallic components, particularly the thimble, by the rotating components of the ball's magnetic moment.

In order to determine $\dot{\omega}$, the change in the time required for a specified number of ball revolutions is measured. The numerical algorithms used to compute $\dot{\omega}/\omega$ differ between the original SRG's and the recently introduced second generation instruments. The difference and its statistical consequences are discussed in Ref. 4. Using the first generation instruments as an example,

$$\frac{-\dot{\omega}}{\omega} = \frac{\tau_{n+1}-\tau_n}{\tau_n\cdot\tau_{n+1}} = \frac{P}{C} + 2\alpha\dot{T} + RD + RN, \tag{2}$$

or

$$P = C\left[\frac{\tau_{n+1}-\tau_n}{\tau_n\cdot\tau_{n+1}} - 2\alpha\dot{T} - RD - RN\right], \tag{3}$$

where τ_n is the time for a specified number of revolutions, τ_{n+1} is the time for the next set of revolutions, and RN is the random noise of the timing circuitry.

From Eq. (3), it is apparent that the SRG is not an absolute gage, but rather an incremental gage with respect to the residual drag. For various smooth ball bearings we have observed residual drags which vary from 1×10^{-4} to 3×10^{-3} Pa N_2 equivalent. The residual drag must be determined and

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subtracted from subsequent measurements as an offset correction. In order to determine the probable random error in measured values of P, we must have some idea of the effects of random noise, of temperature changes, and changes of the residual drag. In practice, this can and should be done by applying "zero" pressure (less than 10^{-6} Pa) to the SRG and observing the indicated pressure or "zero" of the SRG as a function of time. The average value is then entered as an offset correction in the SRG. The changes about that average are a measure of the probable errors. We have found some balls, but by no means all or even most, under measurement conditions specified below, to have residual drags stable to within $\pm 10^{-6}$ Pa equivalent nitrogen pressure over several days' time. Unfortunately, the changes in the SRG zero may occur as truly random noise (susceptible to statistical averaging), or as drifts in the residual drag over times of days, or as infrequent discrete shifts. It is difficult to predict the probable magnitude in the last two cases. We believe the data presented below will not only indicate the range of uncertainties that might be expected, but will also indicate steps that can be taken to minimize SRG errors for a given ball.

III. EXPERIMENTAL RESULTS

All of the data presented were obtained with vacuum systems baked at 230 °C and at pressures below 10^{-7} Pa. These systems were pumped with turbomolecular pumps and cryopumps. The cryopump causes a significant vibration, but preliminary data indicate no significant degradation of the SRG measurements. The laboratory is on a "quiet" basement floor and the room temperature varies no more than ± 0.5 °C. Most of the data were obtained with first generation instruments using a prescale of 6400 (64 000 revolutions per timing period), the longest feasible sampling time. Results are presented in terms of equivalent nitrogen pressure. Since the SRG calibration factor varies with the inverse of the square root of the molecular weight, the results for other gases should be scaled accordingly. All balls were production stainless steel bearing balls. In some cases, attempts were made to increase the magnetic moment in order to improve the signal strength.

IV. RANDOM NOISE

Figure 1 presents the measured zero readings for three different SRG balls. The top two sets were obtained with two different gages on the same apparatus at the same time, so they were exposed to the same environmental disturbances. We believe that the primary reason for the difference in the noise for the three balls is different magnitudes and multipole characteristics of the rotating component of their magnetic moments. However, for some SRG units we have found that preamplifier defects and timing circuitry instabilities made significant contributions to the noise.

Noise will also be generated by mechanical disturbances, particularly those near a resonant frequency of the suspension stabilization circuit. Even lightly touching the apparatus can cause perturbations much larger than the noise levels illustrated in Fig. 1. Low frequency building noise may raise the useful lower limit of the SRG by an order of magnitude

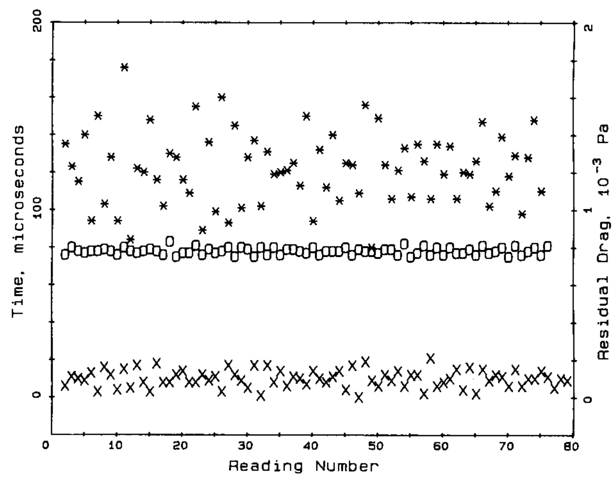

FIG. 1. Residual drag of three different SRG's presented as the time difference for sequential 6400 revolution periods and as nitrogen equivalent pressures. Pressures obtained from the usual average of ten prescale periods would have a scatter 100 times smaller, but the relative difference between the three balls would remain the same.

or more above that found in a quiet environment.

Since the random error of τ_n is independent of the number of revolutions timed, we see from Eq. (3) that the short-term random error of the pressure measurement will vary inversely with the square of the timing period. In the second generation instruments the random errors vary with the negative 2.5 power because of a different data analysis algorithm.[4]

V. TEMPERATURE EFFECTS

Figure 2 illustrates the changes in SRG zero reading caused by inductively braking a ball from 400 Hz to zero, and immediately spinning it back up to 400 Hz. The initial minimum in the data is caused by rapid cooling of the inductively heated stainless steel thimble. The data indicate that a spin up from 0 to 400 Hz causes the ball temperature to rise by about 3 K. This temperature increase decays with a time constant of 70 min. This implies that, for measurements requiring optimum stability ($\pm 10^{-6}$ Pa), at least 5 h should be

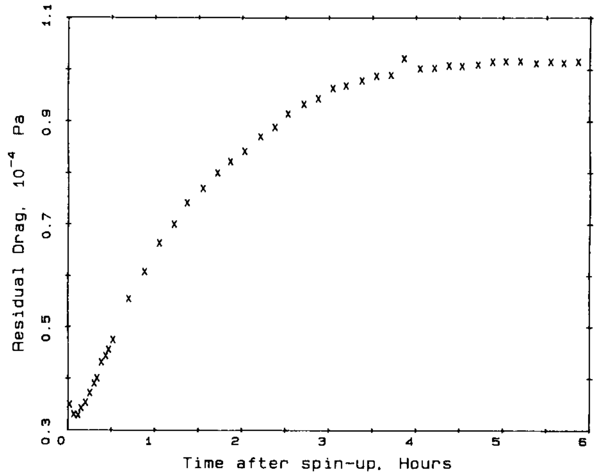

FIG. 2. Change in zero pressure indication or apparent residual drag due to cooling of ball following initial spin up. Approximately 5 h are required for 1×10^{-6} Pa nitrogen equivalent stability.

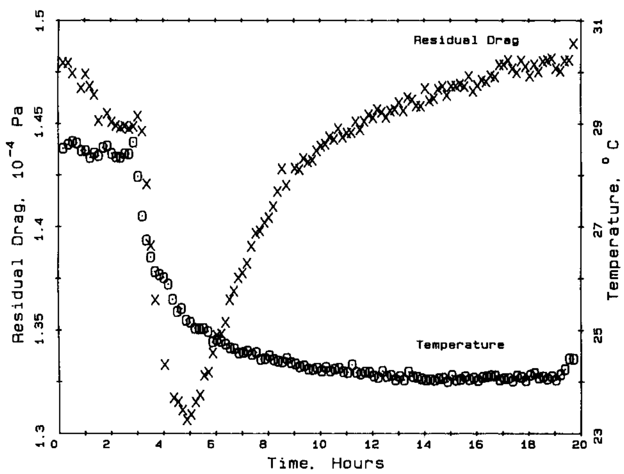

FIG. 3. Effect of temperature change on zero pressure indication or indicated residual drag. ×—indicated residual drag; O—room temperature.

allowed for stabilization after spin up from rest.

The 70 min time constant for thermal equilibrium averages and attenuates short-term random fluctuations in laboratory temperature, but it should be kept in mind that a rate of change of ball temperature of 1 mK/min is equivalent to a nitrogen pressure change of 10^{-6} Pa. The effect of a longer term variation is illustrated in Fig. 3. This figure illustrates the importance of the rate of change of temperature rather than the actual temperature. These data were obtained during a recovery of air conditioning following a maintenance shutdown.

VI. CHANGES IN THE RESIDUAL DRAG

In addition to the electronic noise and temperature perturbations previously discussed, there can be changes in the residual drag. Figure 4 illustrates the change in residual drag of an SRG after the ball was stopped, dropped, and resuspended at about 50 h. Apparently the ball resuspended in a different orientation, changing the magnitude of the rotating magnetic moment. This behavior is quite typical. We have some evidence that partial spin ups of the ball, required when the ball frequency has decayed out of an acceptable range, can also cause significant changes in the residual drag. Apparently the inductive drive signal can cause a slight reorientation of the ball.

Also apparent in Fig. 4, particularly after the discontinuity, is a downward drift in the residual drag with time. This is probably a change with frequency. We have observed strong correlations between frequency and residual drag for some balls. The changes are probably due to reorientation of the spin axis of the ball as it slows down and a consequent change in the rotating magnetic moment. Highly spherical balls perform very poorly in SRG's since the magnetic moment of the ball lines up with the magnetic suspension axis, which is coincident with the spin axis, resulting in a negligible rotating magnetic moment. The asphericity of the less perfect but preferred class III balls helps determine the spin axis and generally results in a usable component of the magnetic moment perpendicular to the spin axis. Unfortunately, the relative importance of the asphericity and the magnetic alignment forces depends on the frequency so that significant changes in the orientation of the ball can occur with frequency.

The residual drag can also be affected by external changes in the magnetic field. As an example, a small sewing needle brought up to the thimble was found to cause significant changes.

VII. EFFECTS OF DATA SMOOTHING

The first generation SRG's employ a running-average data smoothing technique. This reduces the effects of random noise by about a factor of 3, but spreads the effects of any perturbations over the next 29 values of the running average. As a discrete perturbation works its way through the smoothing algorithm, the output is affected in a characteristic manner as illustrated in Fig. 5. These data were obtained with an SRG using the smoothing technique at a nitrogen pressure of 10^{-4} Pa. They can be explained by an 800 μs timing error between the eighth and ninth pressure outputs. Other perturbations, such as a mechanical shock, will cause changes in the output which persist for 29 values after the perturbation.

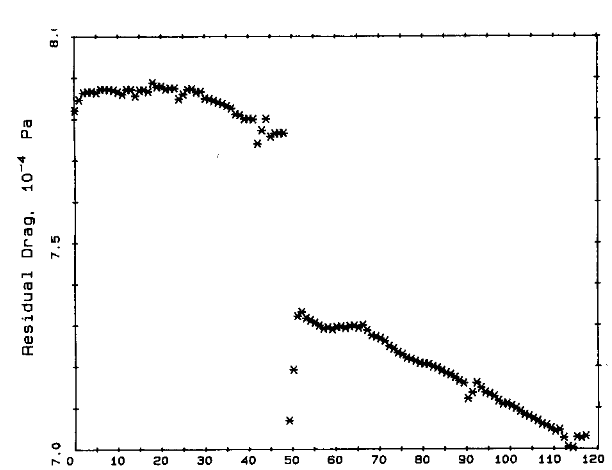

FIG. 4. Discontinuity in the residual drag resulting from dropping and resuspending the ball. The gradual decrease with time of the residual drag is due to reorientation of the ball as the frequency decreases.

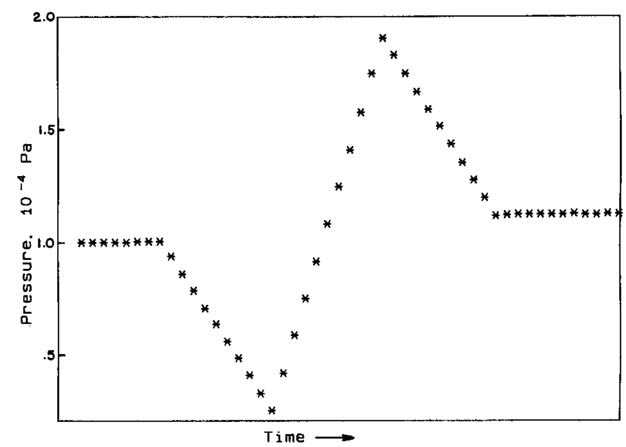

FIG. 5. Effect of an 800 μs timing error between the eighth and ninth data points on the residual drag. The long lasting effect of the error is due to the data smoothing algorithm used in first generation SRG's.

VIII. CONCLUSION

Assuming an adequate vacuum system, the useful lower pressure limit of an SRG will be determined by "zero" stability, or measurement noise, thermal disturbances, and changes in the residual drag. Stability within $\pm 10^{-6}$ Pa nitrogen equivalent pressure is possible under optimum conditions. Some of the steps required to achieve this level of stability are clear: Adequate time (5 h after a complete spin up from zero) must be allowed for thermal stability after the inductive ball drive mechanism is used. The residual drag must be redetermined after each suspension of the ball and should be redetermined just before a set of low pressure observations. Laboratory temperature changes should be minimized. Vibration levels should be minimized. The apparatus should not be touched or disturbed during measurements, mechanical forepumps should be isolated, etc. The external magnetic environment should not be changed. Long sampling or prescale periods must be used to minimize the random noise contribution, particularly at the lowest pressures.

Other requirements for optimum stability are less well defined. Clearly, we need a good signal-to-noise ratio and a frequency-independent residual drag is desirable. We believe these factors are determined by the magnetic structure and shape of the ball, but do not fully understand how to specify these requirements. Different balls can be spun up in air before installation in the vacuum chamber; the SRG pickup signal monitored; and balls with inferior signal strength eliminated. However, signal strength is only one of the important factors and the final selection requires observation of the zero of the SRG for periods long enough to determine not only the random noise, but possible changes with frequency as well. Unfortunately, the signal-to-noise ratio, and possibly the frequency dependence, varies not only from ball to ball, but for some balls it changes when the ball is resuspended. This makes preselection of balls difficult, but this can be put to good use. The signal-to-noise ratio can be changed, sometimes in the positive direction, by slowing the ball to zero, dropping it, and resuspending it. All of this can be a tedious process, but a necessary one if optimum results are to be obtained. All other things being equal, it is desirable to minimize the residual drag. Towards this end, perturbations of the axial symmetry of the field should be minimized. A low permeability material should be used for the thimble—316 L stainless steel appears to be quite satisfactory. Small magnetic objects, such as loose SRG balls, should be kept away from the suspension head as they can fall inside and attach to the permanent magnets. Nonmagnetic materials should be used for any apparatus in close proximity to the SRG ball and suspension head. We have found SRG thimble assemblies with magnetic steel ball retainer clips and suspension head brackets. These should be replaced with nonmagnetic stainless steel.

We believe that in most cases the SRG electronics make a negligible contribution to SRG instabilities. However, on occasion we have observed significant, or even major, electronic instabilities. Apart from the previously mentioned preamplifier and timing circuitry problems, excessive residual drag and noise can be caused by oscillations in the suspension stabilization circuits. These are generally due to mechanical disturbances, but may be due to improper adjustment of the stabilization circuit.

It is also possible for a dc offset to develop in the vertical suspension electronics that will cause excessive current and heating in the suspension head and possible increases in the residual drag due to field asymmetries.

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